Environmental Security Technology Certification Program
Project #200104

Low-Order, Underwater Detonation Study

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14. ABSTRACT

The Environmental Security Technology Certification Program funded the Naval Explosive Ordnance Disposal Technology Division to carry out an underwater, loworder detonation study, Project # 200104. The goal of the project was to develop for civilian UXO companies an alternative means to Blow-in-Place (BIP) procedures for submerged unexploded ordnance (UXO) that was unsafe to move. BIP has been a cause for concern because of the acute environmental damage caused by underwater detonations. The German-produced HL-21 shape charge was selected as a low-order tool because it was commercially available and had a water tightness specification down to 60m. Tests on TNT-filled 155mm projectiles and tritonal-filled Mk 82 bombs at the Aberdeen Test Center Briar Point Test Pond were conducted in June and July 2001. The results showed that low-order detonation procedures were very effective in reducing the blast effects while causing a complete disruption of the ordnance. Pressure histories were equated to equivalent yields in pounds of TNT. The data showed that low-order detonation could reduce yields up to 99 percent over conventional BIP procedures. Bulk explosive and fragmentation were recovered after each low-order trial. The issues of chemical contamination were outside the scope of this effort. Cost performance data is also presented that highlights the expense of using diver-operated tools. Additional testing is recommended to resolve issues with ?no reaction? in tests on Mk 82 bombs, and to broaden the scope to RDX-based explosive fills.

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GLOSSARY OF TERMS

1-D – One dimensional
ATC – Aberdeen Test Center, Aberdeen, MD
BIP – Blow in Place
C4 – a type of explosive
CFR – Code of Federal Regulations
Comp B – a type of explosive
DDESB – DoD Explosive Safety Board
DoD – Department of Defense
EIS – Environmental Impact Statement
EOD – Explosive Ordnance Disposal
ESTCP – Environmental Security Technology Certification Program
Fsw – feet of sea water (water depth)
H-6 – a type of explosive
HL-21 – Nomenclature of a German-produced shaped charge
Imax – Maximum Impulse
mm – millimeter
Mk – Mark (a Military designation to identify equipment and ordnance)
msec - milliseconds
NMFS – National Marine Fisheries Service
Pmax – Maximum peak pressure
RDX – Royal Demolition Explosive, a type of explosive
TNT – trinitrotoluene, a type of explosive
UXO – Unexploded Ordnance

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ABSTRACT

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The German-produced HL-21 shape charge was selected as a low-order tool because it was commercially available and had a water tightness specification down to 60m. Tests on TNT-filled 155mm projectiles and tritonal-filled Mk 82 bombs at the Aberdeen Test Center Briar Point Test Pond were conducted in June and July 2001. The results showed that low-order detonation procedures were very effective in reducing the blast effects while causing a complete disruption of the ordnance. Pressure histories were equated to equivalent yields in pounds of TNT. The data showed that low-order detonation could reduce yields up to 99 percent over conventional BIP procedures. Bulk explosive and fragmentation were recovered after each low-order trial. The issues of chemical contamination were outside the scope of this effort. Cost performance data is also presented that highlights the expense of using diver-operated tools.

Additional testing is recommended to resolve issues with "no reaction" in tests on Mk 82 bombs, and to broaden the scope to RDX-based explosive fills.

Low-Order Detonation Study

Naval EOD Technology Division

January 17, 2002

1 Introduction

1.1 Background

1.1.1 Extent of the Problem

War activities, dumping, accidents, ordnance development, and military training have left significant quantities of unexploded ordnance (UXO) in coastal waters in the United States and abroad. The remediation of UXO from Department of Defense lands has proven to be laborious and expensive, and the limited underwater clearance efforts to date have seen the difficulties magnified due to the challenging operating environment. Consequently, underwater UXO remediation in the United States has been limited primarily to public exigencies. While U.S. Navy Explosive Ordnance Disposal (EOD) forces have the responsibility to respond to these emergencies, they do not have the resources to conduct routine clearances of submerged UXO (Pedersen, 1996). It is expected that civilian companies may be required for any extensive UXO clearances. Submerged UXO may be hazardous to move. A recent *AP wire service* report (February 5, 2001) on the CNN web site noted problems with removing UXO in Hong Kong harbor that included the sinking of a dredge in 1993. There are very few options in dealing with hazardous ordnance that cannot be safely moved.

1.1.2 Current Practice

UXO, deemed unsafe to move, historically has been countercharged or blown-in-place (BIP). BIP procedures involve the sympathetic detonation of UXO by a donor charge. The donor charge weights will vary depending on the UXO and circumstance. Navy divers might typically use 5 pounds of C4 explosive to dispose of a 155mm projectile, and up to 20 pounds of C4 for a Mk 82 bomb. C4 is used because it is a safe explosive to use in a military environment. However, civilian bomb disposal divers (generally retired

Navy divers) would not have the concerns of using explosives that were “bullet-impact safe”, and the expense, accountability, and storage issues of C4 explosives would be cause to consider other explosives. Civilian UXO divers have suggested (private communication) that a 1-pound pentolite booster charge would be an economical means to dispose of a 155mm projectile. The risk of using a small demolition charge is that it may only kick out the ordnance.

1.1.3 Issues

The National Marine Fisheries Service (NMFS) has expressed past concerns over planned BIP procedures as, for example, necessitated by the discovery of UXO at a sewer outfall construction project in Hawaii (Knowles, 2000). In their letter to Pacific Division Naval Facilities Command, NMFS advised the Navy to mitigate potential acute blast damage to turtles and other marine life caused by any BIP actions, including ensuring that the smallest reasonable explosive weights are used to accomplish the procedure. There is a need for alternatives to countercharging submerged UXO that cannot otherwise be moved nor left in place.

1.1.4 An Alternative Approach

Low-order detonation techniques have matured as a means to render safe surface UXO. Several countries offer commercially available tools for civilian organizations to use on UXO. This technology is capable of reducing the net explosive yield by more than 90 percent over conventional BIP techniques. The procedure is not always successful, and the reduction in yield may vary, depending on the low-order procedure, type of ordnance, and its explosive fill. Low-order detonation is generally not used for routine surface UXO clearance, because it will scatter bulk explosive, creating yet another waste stream. There is very little data on generating low-order detonations with UXO underwater. The use of low-order detonation technology has potential to mitigate the acute blast effects of conventional underwater BIP procedures. The success of this project may facilitate the development of work plans by providing an alternative to BIP.

1.2 Official DoD Requirements Statement

1.2.1 Requirement

The Navy Tri-Service Environmental Quality Research Development Test and Evaluation Strategic Plan specifically addresses under Thrust Requirements 1.A.1 and 1.A.2, the requirements for improved detection, location and removal of UXO on land and underwater. The index numbers associated with these requirements are 1.I.4.e and 1.III.2.f. The priority 1 rankings of these requirements indicate that they address existing statutory requirements, executive orders or significant health and safety issues. The requirements document states: There are more than twenty million acres of bombing and target ranges under DoD control. Of particular concern for the Navy are the many underwater sites that have yet to be characterized. Each year a significant portion (200,000-500,000 acres) is returned to a civilian use. All these areas must be surveyed for buried ordnance and other hazardous materials, and certified safe for the intended end use. This is an extremely labor intensive and expensive process, with costs often far exceeding the value of the land…

1.2.2 How Requirements Were Addressed.

This project specifically addressed the development of an alternative means to render safe UXO underwater that is compliant to statutory regulations that direct Federal agencies to minimize environmental damage to marine life and coral reefs.

1.3 Objectives of the Demonstration

The objective of this demonstration was to develop a procedure and validate a low-order technique as an alternative to countercharging submerged UXO. The demonstration investigated the effectiveness and reliability of the (German) HL-21 as a low-order, render safe detonation tool against *unfuzed* 155mm High Explosive (HE) projectiles and MK 82 bombs. Effectiveness was measured by a reduction in the net explosive yield. The equivalent pounds of TNT needed to generate the measured pressure, and impulse determined the net explosive yield of a low-order detonation. (Additional data related to the growth and collapse of the detonation bubble was also gathered, as a result of comments received at the UXO Forum 2001 presentation of the Study in New Orleans). Reliable reductions in explosive yield would afford both Navy EOD and civilian UXO companies greater windows of opportunity for ordnance disposal and minimize the potential risk to the marine environment and public safety.

1.4 Regulatory and Other Issues

The Marine Mammal Protection Act of 1972, as amended through 1997, the Endangered Species Act of 1973, and Executive Order 13089, Coral Reef Protection of June 11 1998, have bearing on current EOD techniques to sympathetically blow-in-place underwater UXO. In those instances where underwater UXO remediation may be attempted, an Environmental Impact Statement (EIS) may be required under the National Environmental Policy Act, Title 40, Code of Federal Regulations (CFR), Parts 1500–1508. The EIS is needed to address the potential consequences of underwater detonations. (The mechanisms by which marine biota are damaged by underwater explosions are beyond the scope of this study). While laws generally allow for the emergency destruction of UXO underwater in the interests of public safety, regulatory laws will affect UXO destruction methodology when the risk to public safety is not time-critical. In addition, Executive Order 13089 requires Federal activities whose actions could impact coral reefs to develop methods to mitigate potential damage. Navy EOD procedures require that a higher-level approval be obtained before the non-emergency detonation of underwater ordnance is attempted outside of pre-approved disposal areas. Generally, the Activity requesting EOD assistance or managing the underwater clearance effort is responsible for ensuring compliance with Federal and State environmental regulations. The approval process may involve local regulatory agencies or fisheries personnel. Regulatory agency decision-makers may require statistical performance data before accepting underwater low-order detonation technology as a viable environmental mitigation technique.

Low-order detonation tools are not 100 percent effective, and the consequences of a high-order detonation must be anticipated. Low-order detonation tool performance varies with the procedure, type of ordnance, and the explosive fill. Two types of ordnance were used in these trials and this will limit the applicability of the test data. Additional controlled tests over a wider range of UXO, and monitoring of the technique in the field against dud-fired UXO may be required to gain confidence in the procedure.

Also, it is likely that bulk explosive and fuzing will remain after a low-order reaction in the field. The need to clean up this explosive waste stream will necessitate additional efforts over what is required for conventional BIP. The management of low-order waste may fall under the considerations of the Comprehensive Environmental Response, Compensation, and Liability Act, Resource Conservation and Recovery Act, Department of Defense Explosive Safety Board (DDESB), Department of Transportation, and State-specific regulations. Accordingly, low-order should be considered primarily when the environmental benefits of blast mitigation exceed the additional costs of cleanup. The issues of explosive chemical residue contamination resulting from low-order detonation were outside the scope of the current study.

1.5 Previous Testing of the Technology

Low-order testing was performed for EOD tool development during Phase II Developmental Test (DT-II) series for the Main Charge Disrupter (MCD) (Gill, 1999). The test program established the MCD as an effective tool for causing low-order reactions in ordnance. The MCD tool is not configured for underwater usage. The effectiveness of the MCD varied with the type of ordnance and the explosive fill; however, the *presence or absence of fuzing* had no affect on performance. Also, there was no appreciable difference in MCD effectiveness on whether test ordnance was from a *magazine or dud-fired*.

2 Technology Description

2.1 Background

2.1.1 Extent of the Problem

War activities, dumping, accidents, ordnance development, and military training have left significant quantities of unexploded ordnance (UXO) in coastal waters in the United States and abroad. The remediation of UXO from Department of Defense lands has proven to be laborious and expensive, and the limited underwater clearance efforts to date have seen the difficulties magnified due to the challenging operating environment.

Low-order detonation research is being conducted in order to develop a better understanding of the phenomenology, and there are still unresolved issues as to what occurs in a "low-order" reaction. In general, ordnance is designed to be insensitive and withstand mechanical and thermal insults, such as would occur from bullet or fragmentation impact. Thus, it is possible to penetrate some UXO with a high velocity projectile and not cause any reaction. Low-order detonation tools are designed to transmit enough reaction energy to the explosive charge so that the case ruptures, but not so much energy as to cause a full detonative reaction. These tools typically use ounce quantities of explosives. The likelihood that the shock of an impinging shaped charge will detonate the explosives in UXO can be characterized by the parameter V^2D, the velocity of the impinging jet squared times the diameter of the jet. With insufficient shock to detonate, the explosive material may react with a rapid burn (deflagration) that may yet transition to detonation, depending on confinement, case material, charge size, and type of explosive. Thus, the consumption of explosive material in a low-order reaction will serve the purpose of reducing the explosive yield. The definition of "low-order" has accordingly been called "any explosive yield less than a full high-order". A 25 percent reduction in explosive yield was used in a research report to qualify low-order detonation tool performance (Gill, 1999). This arbitrary criterion will be maintained as a definition of low-order. It is not unusual to reduce the explosive yield of UXO as determined by the peak pressure by more than 90 percent. Yield reductions based on impulse will be lower because of the slower time of reaction in low-order events.

2.1.2 Low-Order Detonation Tools

Both France and Germany make commercially available, low-order detonation tools with an advertised underwater capability. TWD GmbH of Schrobenhausen, Germany, a subsidiary European Aeronautic Defence and Space Company (EADS), produces the EOD 21 ("Explosive Charge DM27, 18g, EOD SHAPED CHARGE") as a general purpose, low-order detonation "tool". The EOD 21, hereafter "HL-21", its common marketing name, contains 18 grams of explosive (~94 percent RDX). It was selected for this ESTCP study because it was commercially available, had been previously characterized in surface tests (Baker, 1997), and was readily available in the NAVEODTECHDIV magazines in sufficient numbers to carryout the ESTCP Study.

The HL-21 is 32mm diameter x 95mm long, and has a specification of water tightness to a depth of 60m. The tool also has brass decelerator plates available that can be mounted to the front of the shaped charge. Up to three plates may be added to slow the jet down for thin-cased ordnance. (See parts of the Vendor brochure in Appendix C for a depiction of the HL-21 and for additional information). TDW advises using decelerator plates to keep the velocity of the jet below 2160 m/sec at the point of bulk explosive impact.

2.1.3 Underwater, Low-Order Detonation

Preliminary tests with the HL-21 were conducted under the auspices of this ESTCP Study in January 2001 at the Army Research Laboratory's Blossom Point Test Facility in Charles County, MD. The purpose of testing was to establish low-order feasibility and procedures prior to the full-scale instrumented underwater tests scheduled in June/July 2001. Because the HL-21 tool is normally fired in air, it was expected that water would disturb and decelerate the jet. Initial tests against steel witness plates established that adequate penetration was achieved with a 60mm standoff (distance from the front of the tool to the surface of the plate) and a 90-degree angle of attack. Tests were then conducted against 155mm projectiles using partially buried 55-gallon drums filled with water, figure 1. All five tests against 155mm projectiles (TNT-filled, no fuzing) with at least 60 degree angles of attack resulted in successful low-order detonations. (One test at a 45-degree angle of attack resulted in no penetration of the ordnance). Although there was no instrumentation to quantify the yield reduction in these trials, the differences between an intentional high-order detonation and the HL-21-induced low-order detonations on the test fixtures were significant. In one test, the drum was just split open. The low-order detonations of the 155mm generated large-sized fragmentation, with normal edge fracture (at 90 degrees). Unreacted TNT was also present after some shots. In an intentional high order detonation, the drum was completely destroyed, the relatively small 155mm fragmentation had fracture edges at 45 degrees, and no bulk explosive could be found.

Figure 1. Blossom Point Trials

Explosive limits (on the quantity of explosive that could be detonated) at the Blossom Point Test Facility did not permit the testing of HL-21s against Mk 82 Bombs. Since a 155mm projectile had a slightly thicker case than a Mk 82 bomb, penetration was not expected to be a problem.

2.2 Strengths, Advantages, and Weaknesses

The primary advantage of low-order detonation over BIP stems from the mitigation of acute blast effects.

A secondary advantage is that it may be economical to low-order UXO in place instead of moving it to a separate disposal site. The logistical expense of moving underwater UXO would depend on the local conditions, the size and nature of the UXO, and the distances involved.

The disadvantage to low-order detonation is that it will create a waste stream. The decision to lift the waste material and shift it to a safe (permitted) disposal site would need to be addressed in a DDESB Explosive Safety Submission.

2.3 Factors Influencing Cost and Performance

Specific cost and performance factors identified in *Guide to Documenting and Managing Cost and Performance Remediation Projects* are not applicable to low-order detonation procedures. Both BIP and low-order require explosively qualified divers, and the costs of underwater remediation operations are primarily driven by those factors that affect diving. These and other factors that influence performance and costs are identified in the following Table 1.

Table 1. Cost/Performance Parameters

Parameter	Potential Effect on Cost or Performance
Water Depth	Wage premiums for commercial divers increase 25 percent for diving operations below 50 feet, and again below 100 feet. An on-site decompression chamber must be provided to divers, if dive time requires decompression stops, or if the operational depth is greater than 100 feet. Decompression chambers are expensive to mobilize and man. The HL-21 is depth rated to 60m, and may not be effective below that depth.
Water Temperature	Colder water decreases diver time in the water and so increases the labor costs to accomplish a given task. Divers may have to use special equipment (regulators and dry suits), thus increasing capital/operating expenses.
Tidal Current	Higher currents will limit the ability of divers to operate on the seafloor; thus increasing costs to complete a task by limiting operations to “tidal windows”.
Sea State	Support craft must be capable of supporting the dive team. Higher sea states or swell will require larger craft, which have higher expenses.

“Remoteness” of location	Transportation and storage costs of explosives are expected to increase in more remote sites.
Ordnance	The HL-21’s ability to cause low-order detonations and effectively reduce the explosive yield is expected to vary with the type of ordnance and type of explosive loading.

3 Site/Facility Description

3.1 Background

The major factors in site selection were environmental compliance, cost, and an ability to accommodate two hundred-pound-plus underwater explosive shots. The Briar Point UNDEX pond at Aberdeen Test Center (ATC), Aberdeen, MD, has the infrastructure to accommodate complex instrumentation. ATC is a Department of Defense Major Range and Test Facility base (MRTFB).

3.2 Test Facility Characteristics

The Briar Point UNDEX test pond (figure 2) is a man-made facility built primarily for Navy tests that involve the detonation of explosives on the surface or underwater. The pond has a surface diameter of 330 feet, a maximum depth of 60 feet, a flat- surface bottom diameter of 70 feet, and side slopes of 2.5 to 1. The perimeter of the pond is armored with stone to prevent erosion from wave action. The volume of the pond is approximately 84,000 cubic yards of water (17 million gallons). The surrounding soil is comprised mostly of silty clay. The maximum charge weight that can be detonated in the UNDEX pond is the equivalent of 400 pounds of TNT. Because the pond is physically and environmentally isolated from the local water sources, it can support a wide range of tests without inflicting harm to the environment. Briar Point has two launch and recovery facilities designed into the pond.

Figure 2. Briar Point Pond

A marine rail can be used for the launch and recovery of test vehicles up to 500 tons. The pond also contains a working platform or seawall (wetdock) for launching other types of floating vehicles in and out of the water. The 90-foot wide seawall provides a slip area with an average water depth of 17 feet. A crane capable of lifting 100 tons is available. Diver support is available from a team of approximately 25 individuals experienced in underwater video, explosive handling, welding, cutting, salvage, inspection, and search/recovery.

4 Demonstration Approach

4.1 Performance Objectives

The test goal was to measure the reliability and effectiveness of an HL-21 attack on unfuzed ordnance. (As noted earlier, trials with surface ordnance have indicated that the presence or absence of fuzing does not affect low-order detonation tool performance). Reliability in terms of this study refers to the ability of the HL-21 to function properly underwater. A reliability failure would occur if the HL-21 was fired and there was no penetration through the ordnance or witness plate. (Note that this definition has been slightly modified from the original definition in the test plan, so that HL-21 reliability is independent of the type of target, as was the intention). Effectiveness refers to two measures, both related to the explosive event resulting from the HL-21 attack on UXO. One objective is to determine the statistical likelihood of a low-order detonation, given that the HL-21 functioned properly. The second objective is to determine the equivalent explosive weight in pounds-TNT, given that a low-order detonation took place. Related to this measure is the relationship of the explosive yield reduction for low-order detonations over what would have occurred in “normal” BIP procedures. (In this latter case, a 1.4-lb. TNT donor charge will be assumed for a 155mm projectile BIP procedure, and a 5-lb. TNT donor charge will be assumed for a Mk 82 bomb). Explosive yield equivalencies provide an analytical basis to compare performance and average results. Explosive yields were estimated from ATC-gathered pressure histories. NSWC Indian Head interpreted the data for TNT yield equivalency based on pressure, impulse, and bubble characteristics. General performance metrics used to evaluate the low-order detonation tool are presented below in Table 2.

Table 2. Performance Metrics

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)
Quantitative	Reliability (ability to penetrate UXO). Effectiveness (statistical likelihood of a low-order detonation) Effectiveness (percent reduction in yield over BIP procedures)	Pressure history of each event correlated to equivalent explosive yield through peak pressure, impulse, and bubble period modeling.
Qualitative	Reliability	Test observation (plume height, fragmentation evidence).

	Ease of Use	Observation

4.2 Physical Setup and Operation

4.2.1 ATC Briar Point Pond Set-Up

Demonstration set-up included the following major tasks: 1) equipment mobilization, 2) blast shield and firing system layout, 3) instrumentation, and 4) and ordnance preparation. Table 3 lists the equipment and material for the low-order detonation study.

Table 3. Demonstration Equipment and Material

Item Number	Description	Quantity	Remarks
	Ordnance		
1	155mm TNT Projectiles	20	On Station (ATC) - TNT Filled
2	MK 82 GP Bombs	20	NSWC Crane, IN - Tritonal Filled
3	HL-21 Tools	45	NAVEODTECHDIV
4	Blasting Caps	45	On Station
5	Initiation Device	2	On Station
6	HL-21 Positioning Assemblies	40	NAVEODTECHDIV
7	Data Acquisition System	1	BTST –Ballistic Test Site Terminal
8	Video Cameras/Enclosures		
9	Ordnance Suspension Line	1	5/8" Diameter IWRC Nominal Strength = 17.4 Ton
10	Ranging Tower	1	Plume Height Reference On station
11	Instrumentation Support Lines	3	0, 120, 240 Degree Rope (Wire, Polytron,etc)
12	Grip Hoists	1	Minimum
13	Support line Masterlink	1	
14	Cable Buoys	2	As required
15	Cargo (residue) Netting	1	20' x 20'
16	Cargo Net Rigging	2	
17	Anchor Posts	7	As required
18	Dive Air Fill Station	1	
19	Crane	1	Watercraft & Mk82 Deployment
20	Watercraft	1	Bridge Boat, row boat
21	Charge Arming Platform	1	As required
22	Ground Rods	2	Firing & Instrumentation

23	Trailer Shield	1	Instrumentation
24	Class-A Bomb Proof	1	Firing Position
25	Personal Protective Equipment		Life Preservers, Gloves, etc

4.2.1.1 Equipment Mobilization

Main items requiring mobilization included the crane, trailer shield, Ballistics Test Site Terminal (BTST), video camera enclosures, bomb proof, charge arming platform, bridge boat, and dive air station.

4.2.1.2 Blast Shield and Firing System Layout

The trailer shield was used to protect instrumentation equipment during the test. Typically shields are constructed of 0.75 to 1-inch thick steel panels sufficient to deflect most fragmentation and protect equipment. All essential personnel required within the danger zone as approved by Range Safety were protected by Class-A bombproofs. The personnel bomb proof needed to be large enough to accommodate the firing system, remote camera monitors, remote instrumentation equipment, and personnel. A low energy firing system was used. On site, ground rods were used to ensure that appropriate grounding was available for ordnance operations and that separate/independent grounds were available for instrumentation.

4.2.1.3 Instrumentation

An array of gauges at a depth of 24 feet was used along three radii to capture the pressure history of the 155mm projectile and Mk 82 bomb low-order reactions (figure 3). The gauges were placed further away during the Mk 82 trials to better protect them from inadvertent high order detonations. The depth of one sensor set was increased to 29 feet

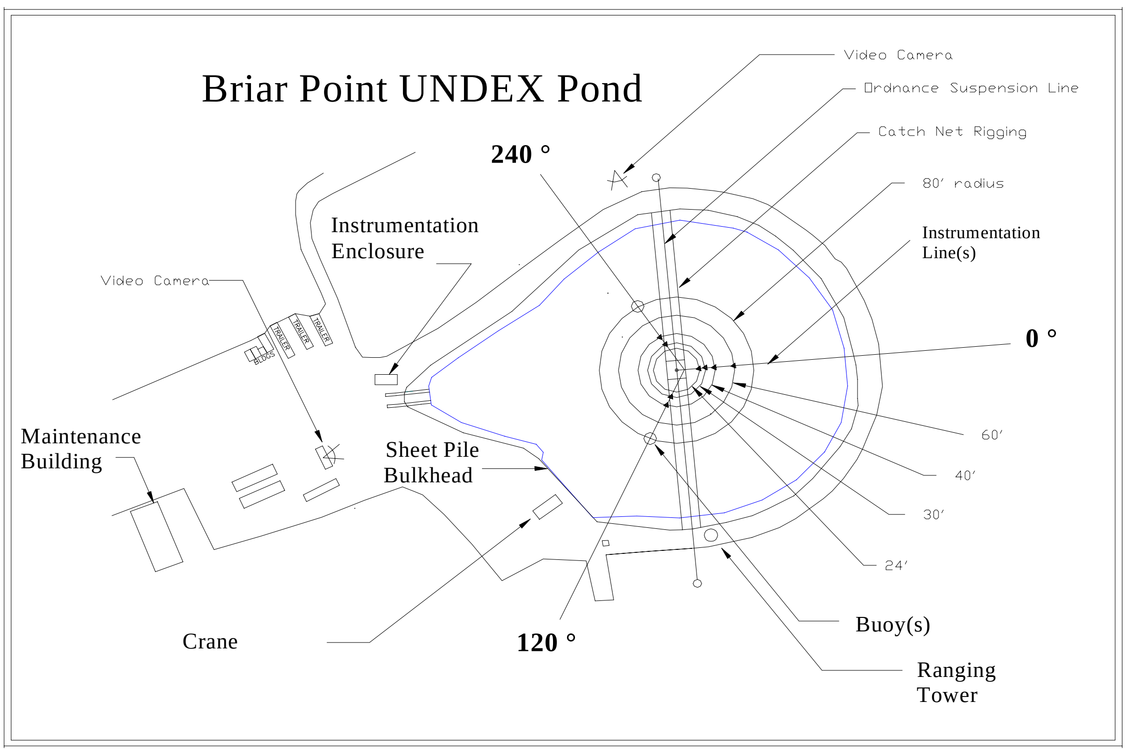

Figure 3. Test Layout

in order to avoid interference from a cable bundle. An additional set of sensors was placed 100 feet away to capture the bubble pulse and bubble period of the low-order detonations (because of commentary received at the 2001 UXO Forum). PCB microsensors and Endevco gauges (models 8511 and 8530) were used. (NSWC Carderock participated in two 155mm shots with their independent tourmaline sensors along the zero degree radii). The instrumentation lines/cables were supported by 1/2-inch diameter cable suspended over the Pond. Support buoys were used to reduce cable tension. The Ballistic Test Site Terminal (BTST) was placed under a trailer shield to protect it. Standard one thousand-foot lengths of instrumentation cable were used to run to all of the gauge locations. ATC instrumentation personnel fabricated gauge supports or stinger assemblies to hang from the instrumentation support lines. Additionally, the sixty-foot high tower on site was marked every 20 feet to provide a plume height reference.

Three real time video cameras were used. One camera was placed on the opposite side of the pond so that the tower markings or graduations and the shot plumes were visible within the field of view. A second camera was positioned to have an unobstructed view to the center of the pond where the ordnance will be suspended. The third camera will be positioned inside the BTST to provide monitoring of the digitizer for signs of potential pre-triggering. No high-speed cameras were used.

4.2.1.4 Data Sampling

- A breakscreen was taped to the ordnance to provide a time zero reference. Pressure-time recordings were taken with a BTST, set for 100 kHz frequency response, and sampling at 800,000 samples per second. A record of 100,000 samples provided a time history of 125 milliseconds in duration for each pressure gage. This permitted recording of the pressure-time history of the initial shock wave. Data from some gauges had to be discarded. The history of the pressure wave was used to calculate equivalent explosive yields for each shot (see Appendix D).

- Case fragmentation and explosive residue from each shot was collected in a 20 by 20 foot cargo net suspended ~40 feet deep, 16 feet underneath the test shot. The fragmentation was photographed. The bulk explosive was weighed; the weight of explosive still attached to ordnance case pieces was estimated. The presence of explosive residue, large fragmentation, and fragmentation fractures at 90 degrees were used to qualitatively assess whether a low-detonation occurred.

- An estimate of the plume height was made for each shot.

4.2.2 HL-21 Procedure

The procedure used to set up the HL-21 for the tests is provided in the last section, Appendix E, as a convenience for the reader to separate from the report.

4.2.3 Analytical Procedures

The purpose of data analysis is to determine whether a low- or high-order event took place. Physical evidence was gathered as discussed in data sampling for a qualitative assessment (Section 4.2.1.4). Equivalent explosive yield calculations were used to provide a quantitative measure of the output of a low-order reaction. The procedures used to compute the equivalent explosive yield were adapted from methods intended to apply to underwater high-order detonation phenomena. This is analogous to methods used to characterize surface low-order detonation effectiveness. However, additional information is available with the bubble created by an underwater explosion, such as "bubble period", a measure of the time for the detonation bubble to grow and collapse to a minimum diameter.

Peak pressure and impulse are parameters associated with explosive shock that are derived or estimated from the recorded pressure history of an underwater explosion. The equivalent amount of TNT that could duplicate these parameters in a high-order detonation can be estimated by empirical calculation (Similitude) or by analytical methods (1-D Euler). The 1-D Euler method can also be used to estimate equivalent explosive weight from the bubble phenomena derived from the recorded pressure history. Prior to this ESTCP Study, underwater low-order detonation was largely regarded as an anomaly to be avoided. Low-order detonations lack the rapid rise and exponential decay of pressure that is characteristic of high-order detonations. Consequently, the different pressure history parameters will provide different estimates for the equivalent yield. For example, the (relatively) slow rise and fall of pressure in a low-order detonation results in higher computed yields for impulse than expected for the peak pressure associated with the impulse trace. The limitations of using high-order detonation analytical "tools" to characterize low-order detonation performance are left for the reader to judge. See Appendix D for additional discussion on the analytical methodology and assumptions.

The planned procedure to compute yields for each of the three radii with instrumentation was abandoned in favor of computing the yield based on all gauges at a given range. Dr. Wardlaw, NSWC Indian Head, took the following approach to compute equivalent yield:

Part I.

Construct a table of:

a) Maximum experimental shock pressure
b) Maximum experimental shock impulse
c) Maximum experimental bubble pressure
d) Maximum experimental bubble impulse
e) Bubble period

1). Remove data from obviously bad channels;

2). All pressure and impulse traces were compared at each standoff, without regard to direction; the median, not average or maximum values were used.

Part II.

Compute an equivalent weight of TNT for each test based on similitude:

a) Maximum shock pressure
b) Maximum shock impulse

1). Construct by 1-D Euler computation tables of maximum pressure and impulse for the shock phase.

2). Construct by 1-D Euler computation tables of maximum pressure and impulse for the bubble phase.

5 Performance Assessment

5.1 Performance Data

The HL-21 was used 48 times in the course of the study and functioned properly 47 times for a reliability of ~94 percent at the 80 percent confidence level. In one test, the HL-21 jet broke apart and failed to penetrate a Mk 82 bomb.

5.1.1 155mm Projectile Results

The HL-21 was able to induce a low-order detonative reaction in 155mm projectiles 21 times in 21 attempts using a 60mm standoff and angle of attack at least 60 degrees. This procedure was 92 percent reliable at the 80 percent confidence level. Table 4 details the data, which includes the six non-instrumented, procedure developmental shots in barrels of water (155mm A-F) conducted at Blossom Point. One non-instrumented shot

Table 4. 155mm Test Results

Test #	Date	Angle of Attack	Result
155mm-A	1/24/01	90 deg	Low-Order
155mm-B	1/24/01	90 deg	Low-Order
155mm-C	1/24/01	90 deg	Low-Order
155mm-D	1/25/01	45 deg	No Penetration
155mm-E	1/25/01	60 deg	Low-Order
155mm-F	1/25/01	90 deg	Low-Order
155mm-3	6/22/01	90 deg	Low-Order
155mm-4	6/25/01	90 deg	Low-Order
155mm-5	6/25/01	90 deg	Low-Order
155mm-6	6/25/01	90 deg	Low-Order
155mm-7	6/25/01	90 deg	Low-Order
155mm-8	6/26/01	90 deg	Low-Order
155mm-9	6/26/01	90 deg	Low-Order
155mm-10	6/26/01	90 deg	Low-Order
155mm-11	6/27/01	90 deg	Low-Order
155mm-12	6/27/01	90 deg	Low-Order
155mm-13	6/27/01	90 deg	Low-Order
155mm-14	6/28/01	Intentional High-Order (H-O)	
155mm-15	6/28/01	Intentional High-Order (H-O)	
155mm-16	6/28/01	90 deg	Low-Order
155mm-17	6/29/01	90 deg	Low-Order
155mm-18	6/29/01	90 deg	Low-Order
155mm-19	6/29/01	90 deg	Low-Order
155mm-20	6/29/01	90 deg	Low-Order

(155mm-D) with a 45-degree angle of attack resulted in no penetration of the projectile and “no-reaction”.

Test # 155mm-1 and -2, not listed in the above table, were HL-21 tests against steel witness plates and the tool performed satisfactorily. Test # 155mm-14 and -15 were *intentional* high-order detonations induced by packing the nose cavity of the projectile with C-4. Figure 4 shows a typical 155mm projectile low-order detonation, with complete disruption of the round. The fragments could be assembled into the complete round.

Figure 4. Typical 155mm Projectile Low-Order Test Result

Explosive yield calculations varied with the pressure history parameter and analytical methodology. All analytical methods showed that low-order detonation is quite effective in reducing the energy released into the environment over conventional BIP (with a 1.4# TNT-equivalent charge). Table 5 summarizes the reduction in yield for each calculation methodology relative to BIP.

Table 5. 155mm Projectile Equivalent TNT Weight Calculations (lbs. TNT)

Test #	Shock				Bubble		Bubble Period
	Pmax		Imax		Pmax	Imax	
	1D Euler	Similitude	1D Euler	Similitude	1D Euler	1D Euler	1D Euler
155mm-3	0.406	0.166	2.129	5.493	0.176	1.108	3.528
155mm-4	0.292	0.069	1.639	4.074	0.185	0.855	1.815
155mm-5	0.268	0.055	1.926	4.906	0.181	0.98	2.181
155mm-6	0.283	0.066	1.755	4.414	0.182	0.829	1.812
155mm-7	0.309	0.088	2.272	5.891	0.185	1.027	2.236
155mm-8	0.273	0.055	1.532	3.772	0.183	0.8	1.555
155mm-9	0.276	0.061	1.733	4.36	0.222	0.88	1.599
155mm-10	0.364	0.135	2.866	7.567	0.182	1.376	3.285
155mm-11	0.381	0.149	3.732	9.921	0.182	1.433	3.217
155mm-12	0.301	0.075	1.968	5.033	0.192	0.89	1.711
155mm-13	0.333	0.11	2.964	7.781	0.172	1.217	2.538
155mm-16	0.406	0.168	3.071	8.119	0.179	1.152	2.737
155mm-17	0.345	0.135	1.374	3.406	0.179	1.288	2.17
155mm-18	0.325	0.117	1.178	2.894	0.229	0.811	1.909
155mm-19	0.438	0.188	1.677	4.286	0.263	1.203	2.892
155mm-20	0.416	0.182	1.415	3.547	0.179	0.929	2.291
Avg	0.338	0.114	2.077	5.341	0.192	1.049	2.342
Std Dev	0.057	0.048	0.722	2.003	0.025	0.209	0.629
% of 14.6#	2.3%	0.8%	14.2%	36.6%	1.3%	7.2%	16.0%
% of 16# (BIP)	2.1%	0.7%	13.0%	33.4%	1.2%	6.6%	14.6%
Reduction (over BIP)	97.9%	99.3%	87.0%	66.6%	98.8%	93.4%	85.4%

The three times difference in average yield (5.4 ounces of TNT vs. 1.8 ounces of TNT) calculated by 1-D Euler and Similitude using peak pressure (Pmax) has to be considered in context that the yield reductions for both methods exceed 97% over what would have been expected for BIP (16 pounds). Impulse (Imax) calculations showed higher yields over those calculated for Pmax, and the differences between the two analytical methodologies are reversed (2.1 pounds vs. 5.3 pounds TNT equivalent). Bubble period calculations provide intermediate estimates of yield over those calculations based on peak pressure and impulse. All estimates exceed the 25% reduction in yield that was used to arbitrarily define “low-order”.

Divers gathered fragmentation and TNT residue after each instrumented test. The presence of unreacted TNT and large fragmentation after a test provided physical evidence of a low-order detonation. The loose explosive was weighed and the weight of TNT bound to fragmentation was estimated (Table 6). It was generally possible to reconstruct the projectile from the recovered fragmentation. On average, about 25% of the original explosive fill was recovered after a low-order detonation. The possibility of residue from one test being recovered on a following test could not be ruled out. There was no way to determine how much explosive residue was not caught in the cargo net. It took approximately twenty minutes for divers to recover the residue and fragmentation from the 20 x 20-foot cargo net suspended 16 feet below the test shot. Divers took an

Table 6. Recovered TNT Residue (lbs)

Test #	Observed Result	Loose TNT (lbs)	Estimated Bound TNT (lbs)	Total TNT Recovered (lbs)
155mm-A	Low-Order	(non-instrumented test at Blossom Point)		
155mm-B	Low-Order	(non-instrumented test at Blossom Point)		
155mm-C	Low-Order	(non-instrumented test at Blossom Point)		
155mm-D	No Penetration	(non-instrumented test at Blossom Point)		
155mm-E	Low-Order	(non-instrumented test at Blossom Point)		
155mm-F	Low-Order	(non-instrumented test at Blossom Point)		
155mm-3	Low-Order	1.4	0	1.4
155mm-4	Low-Order	4.3	0	4.3
155mm-5	Low-Order	1.6	0	1.6
155mm-6	Low-Order	5.5	0	5.5
155mm-7	Low-Order	3.3	0	3.3
155mm-8	Low-Order	5.1	2	7.1
155mm-9	Low-Order	4.0	2	6.0
155mm-10	Low-Order	1.4	0	1.4
155mm-11	Low-Order	1.6	0	1.6
155mm-12	Low-Order	5.3	0	5.3
155mm-13	Low-Order	1.5	0	1.5
155mm-14	Intentional H-O	0.0	0	0.0
155mm-15	Intentional H-O	0.0	0	0.0
155mm-16	Low-Order	2.8	0	2.8
155mm-17	Low-Order	5.1	0	5.1
155mm-18	Low-Order	5.2	0	5.2
155mm-19	Low-Order	2.0	0	2.0
155mm-20	Low-Order	4.2	0	4.2
Average (Low-Order Only)		3.4	--	3.6

average of 32 minutes to recover the fragmentation from the intentional high-order detonations.

The plume heights of successful low-orders were visibly different from the intentional high-order detonations of the 155mm projectiles, and are additional physical evidence of low-order detonations. The plume height data is shown in the following Table 7. The plume heights correspond somewhat to the yield calculations.

Table 7. Plume Heights (ft)

Test #	Observed Result	Surface Effects/ Plume Height (ft)
155mm-A	Low-Order	N/A
155mm-B	Low-Order	N/A
155mm-C	Low-Order	N/A
155mm-D	No Penetration	N/A
155mm-E	Low-Order	N/A
155mm-B	Low-Order	N/A
155mm-3	Low-Order	Surface Bubbles
155mm-4	Low-Order	Surface Bubbles
155mm-5	Low-Order	8
155mm-6	Low-Order	3
155mm-7	Low-Order	4
155mm-8	Low-Order	3.5
155mm-9	Low-Order	0.5 Spray Dome
155mm-10	Low-Order	11
155mm-11	Low-Order	5.5
155mm-12	Low-Order	4
155mm-13	Low-Order	9
155mm-14	Intentional H-O	23
155mm-15	Intentional H-O	42
155mm-16	Low-Order	4
155mm-17	Low-Order	5.5
155mm-18	Low-Order	4
155mm-19	Low-Order	5
155mm-20	Low-Order	3.5

5.1.2 Mk 82 Bomb Results

The HL-21 was able to induce a consistent low-order reaction in the tritonal-filled Mk 82 bombs after several adjustments in the standoff. All bombs were x-rayed prior to the trials, but no correlation of the test results with the x-rays was apparent. Table 8 lists the complete test series and test results. Initial tests using a 60mm standoff resulted in (4) "no-reaction" test results in the first (9) shots. The no-reactions were characterized by a small hole (~0.1 inch diameter) in the bomb, which otherwise remained intact. Clearly the HL-21 did not impart enough energy into the explosive to initiate the low-order reaction. A foam spacer and then a vaseline-filled vial were used in the 60mm water gap to try to get low-order reactions in tests MK82-8 and -9. (The foam was compressible and it was not used again because water depth could affect its effectiveness). Initially, the bombs were attacked again, but concerns were raised that water would get into the void as an uncontrollable test parameter. The decision was made not to re-use bombs. An exception to this occurred with Test MK82-21, when the HL-21 did not properly function and the bomb case (#30) did not appear to be breached. The HL-21 clearly left two small penetrations in the bomb case, indicating that the jet broke apart before impacting the ordnance. The second attack on the bomb resulted in a no-reaction, and the bomb was retired from the test program. The HL-21 standoff of 30mm resulted of a high-order detonation, the first in the test program. The gap was widened to 33mm and

Table 8. Mk 82 Test Results

Test#	Bomb #	Date	Standoff	Results
MK82-1	11	7/11/01	60mm	Low Order
MK82-2	12	7/12/01	60mm	No Reaction
MK82-3	12	7/12/01	60mm	Low Order
MK82-4	22	7/13/01	60mm	Low Order
MK82-5	23	7/13/01	60mm	Low Order
MK82-6	21	7/16/01	60mm	No Reaction
MK82-7	21	7/16/01	60mm	No Reaction
MK82-8	21	7/16/01	60mm (Foam)	Low Order
MK82-9	1	7/17/01	60mm (Vaseline)	No Reaction
MK82-10	1	7/17/01	50mm	No Reaction
MK82-11	1	7/17/01	45mm	No Reaction
MK82-12	3	7/18/01	30mm	High Order
MK82-13	5	7/18/01	45mm	No Reaction
MK82-14	31	7/18/01	39mm	No Reaction
MK82-15	24	7/18/01	35mm	Low Order
MK82-16	10	7/23/01	33mm	Low Order
MK82-17	4	7/23/01	33mm	Low Order
MK82-18	2	7/23/01	33mm	Low Order
MK82-19	19	7/24/01	33mm	Low Order
MK82-20	14	7/24/01	33mm	Low Order
MK82-21	30	7/24/01	33mm	Malfunction
MK82-22	30	7/24/01	33mm	No Reaction
MK82-23	15	7/24/01	33mm	High Order
MK82-24	28	7/25/01	33mm	Low Order
MK82-25	27	7/25/01	33mm	No Reaction
MK82-26	20	7/25/01	33mm	Low Order

this provided the most consistent low-order response, minimizing the risk of no reaction and high-order detonation.

Using 33 or 35mm standoffs resulted in 8 low-order reactions in 11 trials, discounting Test MK82-21 when the tool malfunctioned. Test MK82-23 did result in a high-order detonation. Figure 7 shows the results of Mk 82 low-order test, with near complete disruption of the bomb.

Figure 5. Typical Mk 82 Bomb Low-Order Test Result

Explosive yield calculations for Mk 82 bombs did vary with the analytical methodology, but the TNT-equivalent yields were so small relative to the main charge (192# tritonal, equivalent to 243# TNT) as to make the differences inconsequential. Yield calculations (#TNT equivalency) for the 13 low-order detonations (Table 9) showed that low-order detonation significantly reduces the energy released into the environment over conventional BIP (assuming a 5# TNT-equivalent donor charge).

Table 9. Mk 82 Yield Calculations (#TNT equivalency)

Test #	Shock				Bubble		Bubble Period
	Pmax		Imax		Pmax	Imax	
	1D Euler	Similitude	1D Euler	Similitude	1D Euler	1D Euler	1D Euler
MK82-1	0.324	0.134	3.114	8.075	--	--	--
MK82-3	0.300	0.113	1.839	4.580	0.382	1.212	4.416
MK82-4	0.310	0.111	2.266	5.835	0.441	1.443	4.830
MK82-5	1.821	1.101	8.684	23.299	0.460	3.020	12.929
MK82-8	0.267	0.051	3.662	9.620	0.415	1.284	4.717
MK82-15	0.285	0.081	2.477	6.412	0.363	1.136	5.041
MK82-16	0.229	0.029	0.533	1.107	0.395	0.646	1.111
MK82-17	0.390	0.172	2.693	6.972	0.404	5.232	4.672
MK82-18	0.268	0.060	1.941	4.888	0.435	1.249	3.737
MK82-19	0.914	0.503	5.277	14.038	0.558	2.283	7.553
MK82-20	0.296	0.079	1.622	3.958	0.349	1.195	3.176
MK82-24	0.225	0.020	1.135	2.680	0.341	0.783	3.394
MK82-26	0.218	0.019	0.525	1.092	0.320	0.519	1.775
Avg	0.450	0.190	2.751	7.120	0.405	1.667	4.779
Std Dev	0.450	0.301	2.200	6.004	0.064	1.319	3.051
% of 243#	0.2%	0.1%	1.1%	2.9%	0.2%	0.7%	2.0%
% of 248# (BIP)	0.2%	0.1%	1.1%	2.9%	0.2%	0.7%	2.0%
Reduction (over BIP)	99.8%	99.9%	98.9%	97.1%	99.8%	99.3%	98.0%

As with the 155mm projectile testing, Imax calculations using Similitude showed the least reduction in explosive yield. Again the yields calculated with 1-D Euler and Similitude reverse relative magnitude with the Pmax and Imax parameters. Bubble period calculations provide an intermediate estimate of yield between peak pressure and impulse calculations. The yield equivalencies for the two unintentional high-order detonations were not calculated.

Divers recovered significant quantities of tritonal explosive residue after each low-order test. They took an average of 25 minutes to recover fragmentation and residue from low-order events, and an average of 42 minutes to recover the fragmentation from the two high-order detonations. The presence of unreacted explosive provided physical evidence of a low-order reaction. The weights of recovered loose and bounded tritonal are presented in Table 10. In some tests, significant quantities of tritonal remained bound in the nose portion of the bomb. On average, over 70% of the 192 pounds of explosive fill was recovered after each low-order detonation.

Table 11. Recovered Tritonal Residue (lbs)

Test #	Observed Result	# Loose Tritonal	Est. # Bound Tritonal	Total # Recovered
MK82-1	Low Order	121.6	10	131.6
MK82-3	Low Order	110.1	20	130.1
MK82-4	Low Order	132.5	5	137.5
MK82-5	Low Order	147.1	20	167.1
MK82-8	Low Order	100.4	40	140.4
MK82-12	High-Order	0	0	0
MK82-15	Low Order	120.2	0	120.2
MK82-16	Low Order	128.7	0	128.7
MK82-17	Low Order	137.8	0	137.8
MK82-18	Low Order	165.8	0	165.8
MK82-19	Low Order	87.3	75	162.3
MK82-20	Low Order	112.9	25	137.9
MK82-23	High-Order	0	0	0
MK82-24	Low Order	78.3	0	78.3
MK82-26	Low Order	110	60	170
	Average	119.4	19.6	139.1

The plume heights of low-order detonations were visibly different form the inadvertent high-order detonations of the Mk 82 bomb. The plume height data is provided in the following Table 11.

Table 10. Plume Heights (ft)

Test #	HL-21 Standoff	Observed Result	Surface Effects/ Plume Height (ft.)
MK82-1	60mm	Low Order	4
MK82-3	60mm	Low Order	2.5 Spray Dome
MK82-4	60mm	Low Order	5
MK82-5	60mm	Low Order	5
MK82-8	60mm (Foam)	Low Order	1.0 Spray Dome
MK82-12	30mm	High Order	85
MK82-15	35mm	Low Order	8
MK82-16	33mm	Low Order	10
MK82-17	33mm	Low Order	1
MK82-18	33mm	Low Order	2
MK82-19	33mm	Low Order	4
MK82-20	33mm	Low Order	8
MK82-23	33mm	High Order	85
MK82-24	33mm	Low Order	14
MK82-26	33mm	Low Order	6

The plume heights for low-order detonations do not correspond well to the respective calculations for explosive yield. For example, Test MK82-5 had the highest computed yield for the low-order successes, yet it did not have the highest plume.

5.2 Data Assessment

5.2.1 Data Analysis

The 8 parameters used to determine yield for each test varied with the parameter selected (maximum pressure, maximum impulse, bubble pressure, bubble impulse and bubble period), and the analytical method (1-D Euler and Similitude). Because low-order detonation phenomena have just recently come under scrutiny, there is no referee to determine which methodology is the more correct representation of yield. All data is presented so that readers may exercise their judgement as to what might be applicable. The physical evidence of low-order (recovered explosive residue, large fragmentation, and low plume heights) correlated well to reduced yields vs. evidence of high-order events (no explosive residue, small fragmentation, and high plume heights).

It is not surprising that the "yield reduction" numbers vary with the selected parameter. Analysis of the experimental data and generation of the equivalent weight is complicated by the differences between the low- and high-order pressure histories. Figure 6 depicts the pressure-time trace of a low-order detonation and an intentionally induced high-order detonation.

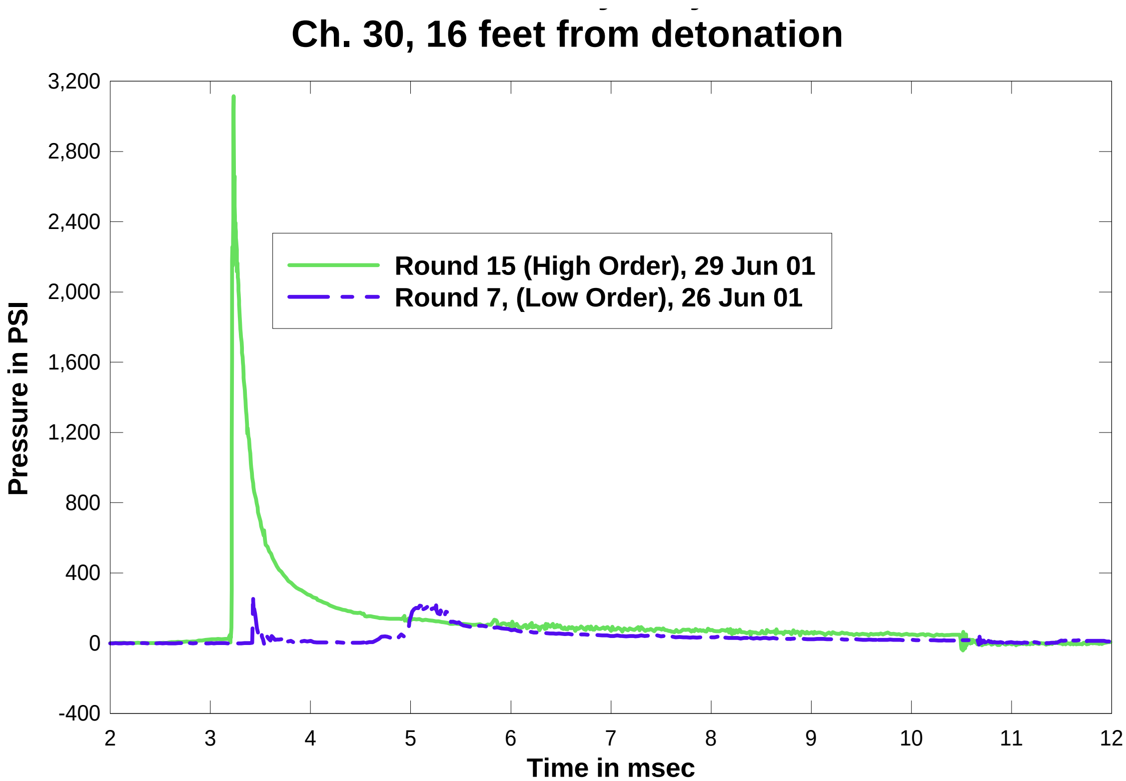

Figure 6. Pressure Time Histories of 155mm Projectile High- and Low-Order Detonations

The pressure pulse from the HL-21 (the first small peak with a rapid rise time, Round 7) is followed ~2 milliseconds later by the low-order detonation of the 155mm. The low-order detonation is characterized by a gradual build up of pressure and slow decay, compared to the high-order detonation with its near instantaneous build up of pressure (at 3 milliseconds) and rapid exponential decay. A consequence of this difference is that the equivalent weight of TNT with respect to peak pressure differs from that computed with respect to maximum momentum. The TNT equivalent weight based on pressure is much lower than that based on impulse. The two analytical methods (1-D Euler and Similitude) show greater disagreement for impulse calculations (pounds of TNT) than they do for peak pressure calculations (ounces of TNT). The Euler solution is not encumbered by an assumed pressure distribution, and the maximum impulse occurs when the pressure decays to the ambient level. The reliability of Similitude impulse figures is questionable, since the Similitude impulse is based on an approximate pressure history curve. Also, the energy released during low-order events appears to fluctuate from one test to another. The combination of these factors produced variation in the equivalent TNT estimates.

Regardless of the parameter or analytical methodology, quantitative analysis showed significant reductions in the explosive energy released into the environment as a consequence of low-order reactions. It should also be noted that the differences in low-order yield impulse calculations between the two ordnance items was not large, only ~30 percent, in spite of a factor of 15 difference in their respective bulk TNT-equivalent weights. This result shows that low-order detonation yields are not directly proportional to the quantity of explosive present. Accordingly, low-order detonation yields for ordnance larger than Mk 82 bombs may also be relatively small. Note that this relationship is only for TNT-based explosive fills.

5.2.2 Instrumentation

The yield calculations from ATC instrumentation did show variance with distance from the shot, and that is believed attributable in part to the instrumentation. Figure 7 shows the calculations of equivalent weights of TNT at the various ranges using Similitude (Pmax) for a 155mm projectile test. The variation of equivalent weight within a given range and the variation with range are evident in the figure. Note that data for all three axes is presented at the given ranges. NSWD Carderock provided their state-of-the-art instrumentation (tourmaline gauges) for two of the 155mm projectile tests along *one* axis,

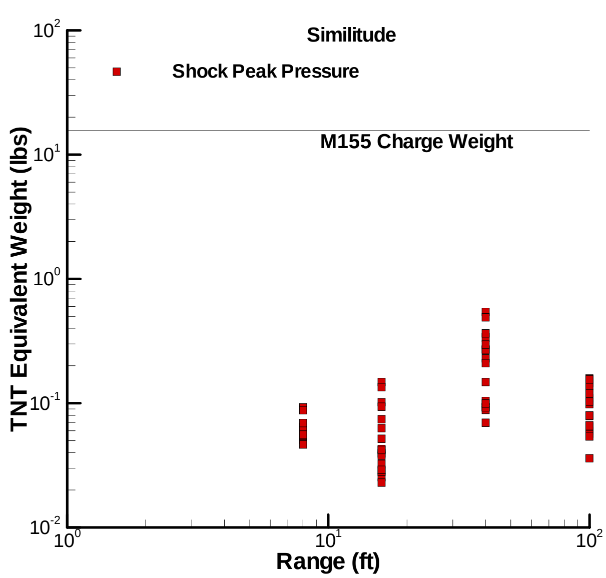

Figure 7. Equivalent Weight as a Function of Range

the zero axis line. Their data using Similitude for the equivalent weight computation (Pmax) for both tests is shown in figure 8. Note that the y-axis is the ratio to 15# TNT equivalent. The variation with range is minimal

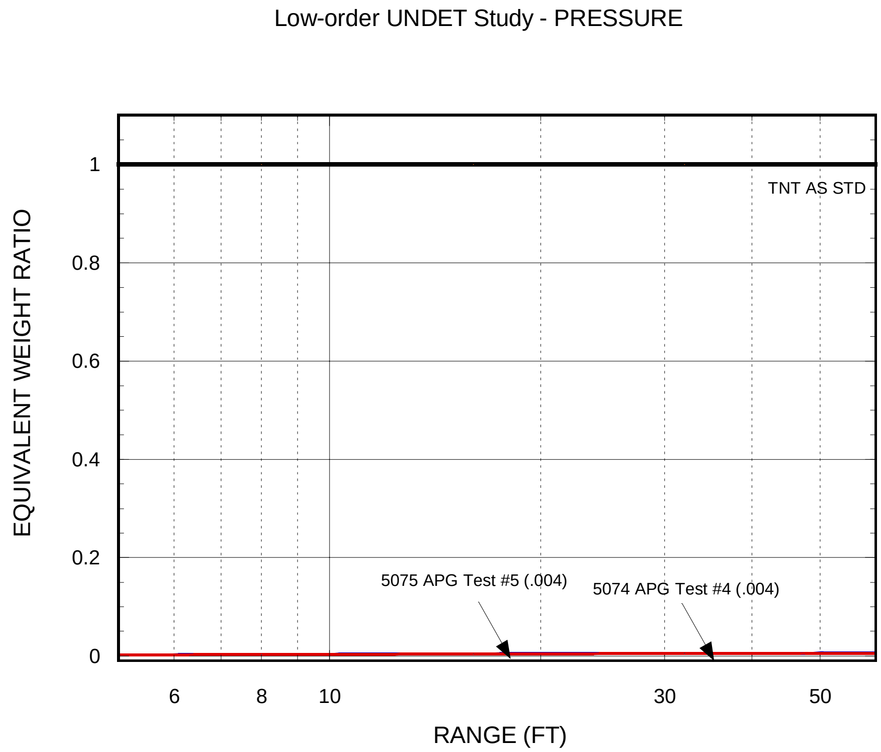

Figure 8. NSWC Carderock, Equivalent Weight *Ratio* vs. Range

The expense of using the higher quality instrumentation was not justified at the time when the success of the project was uncertain.

The ATC instrumentation was not accurate enough to distinguish variance in output along the three radials that were instrumented. Because the equivalent yields of low-order events are so low, there may not be much point in trying to distinguish the (apparently) small differences. It is recommended that any future tests use instrumentation along a single radial in order to reduce the expense of test set up and data analysis.

5.2.3 Data Gaps

Future testing should be conducted to address the no-reaction events that occurred with the Mk 82 bombs. It is possible that two HL-21s (recommended by the manufacturer) at a suitable standoff could increase the likelihood of a low-order reaction, without increasing the likelihood of a high-order detonation.

The explosive residue bound within the nose of a fuzed bomb that had undergone a low-order event would constitute a hazard. This residue varied in estimated weight from 5 to 75 pounds. It is possible that using two HL-21s could reduce the explosive residue, if not eliminate it altogether, at the expense of a slight increase in explosive yield. Additional tests are needed to prove this supposition.

The type of main charge explosive affects low-order reliability and effectiveness. The testing was conducted against TNT-based explosives. Additional tests are needed against RDX-based explosive fills, e.g. Comp B and H-6, to prove the utility of the technique against a broader range of UXO.

Divers were able to recover much explosive residue, as the material did not travel from the shot. Nonetheless, the issue of explosive residue introduced into the environment by low-order techniques needs to be addressed. On-going research suggests that low-order detonation is a significant source of explosive chemical contamination on ranges. Outside study is necessary to determine the environmental consequences of underwater explosive residue remaining from low-order detonations.

5.3 Technology Comparison

Civilian EOD technicians would naturally prefer to use BIP over low-order, as it does not create an additional waste stream and there is no question about the safety of the technique. However, BIP can affect marine biota at a considerable distance from the shot, and thus falls under a variety of laws and regulations enacted to protect the environment. The analysis of pressure histories in this study has demonstrated that the use of low-order detonation technology offers a methodology to mitigate the acute underwater blast effects otherwise associated with conventional Blow-in-Place procedures. Biological response to the pressure and impulse generated by a low-order detonation has not been investigated. Biological damage to marine life has been reported as being proportional to the peak pressure and/or impulse generated by a high-order underwater explosion (Young, 1991). The calculations for safe standoff distances from underwater explosions use “TNT equivalency” and are based on an estimate of 90 percent chance of survivability. Empirical scaling laws take the form:

$$R = k\ w^{a}$$

Where:

R is the safe standoff distance in feet

k is a scaling factor dependent upon the species (e.g. k = 560 for turtles, 578 for dolphin calves)

w is the net explosive weight (n.e.w.) in pounds (TNT equivalent)

a is an exponential decay factor
(e.g. a = 0.333 for turtles, 0.28 for dolphin calves)

Thus, for a 155mm projectile with 14.6 pounds TNT and the use of a 1.4-pound donor BIP charge, the safe standoff for sea turtles would be estimated at ~1400 feet. The safe standoff distance using a low-order detonation tool would be ~300 feet, if it succeeded in reducing the explosive yield of BIP (projectile plus donor explosive) by 99 percent and *if the biological response to low-order detonations can be reliably expressed in TNT equivalency*. The smaller radius would mean an approximate 95 percent reduction in the volume of water affected by the blast. The reduced volume of affected water would result in a smaller “take” of turtles that might otherwise go unobserved within the danger zone. Cratering and other blast effects would also be significantly reduced. Post-blast surveillance by divers (generally required) for affected biota would be easier to accomplish within the reduced volume of affected water.

It cannot be determined within the scope of this study whether low-order detonation yield calculations would either under- or over-estimate the damage radius as represented by these empirical equations. However, the unique pressure history data of low-order detonations is now available, should specific damage mechanisms ever be determined.

6 Cost Assessment

6.1 Cost Performance

The purpose of this section is to identify the major cost elements of underwater explosive operations. The expected operational cost elements for conducting low-order remediation of UXO evolve primarily around diver operations, explosive operations, and environmental and safety surveillance. There is also the added cost of getting an approved Explosive Safety Submission through the Department of Defense Explosive Safety Review Board as to how demolition and explosive materials will be handled and controlled, along with related regulatory environmental compliance issues, impact statements, etc. The cost of the HL-21 hardware is negligible in comparison to these major cost factors. The following figures are based on discussions with commercial companies and government activities involved with underwater operations or with explosive operations.

6.1.1 Dive Operations

Federal OSHA regulations (29 CFR 1910, Subpart T) mandate safe practices for commercial diving companies. Each state has an administrative code that may impose additional regulations. Commercial EOD diving companies typically base their operating procedures on the US Navy Dive manual. Consequently, a minimal dive team is composed of four divers. The dive team will require diving equipment (suitable to the expected temperatures) and dive support equipment (boat charter and decompression chamber support). Federal regulations, 29CFR Part 5, Subpart A – Davis Bacon and Related Acts and Procedures, govern the labor costs of divers. Cost per diver in wages and fringe benefits is $72/hour; G&A and overhead would ~double the cost to $144/hour. Labor rates will increase 25% for depths greater than 50 fsw and increase another 25% for depths greater than 100 fsw. Divers will require a dive boat with crew of sufficient size to carry all their equipment and to shelter them from the environment. If the expected depth/duration of a dive is expected to require decompression, then a decompression chamber must be provided on-site (if not otherwise accessible) with qualified personnel, at an estimated cost of $1200/day (Global Divers, LA).

The cost to conduct one day of dive operations (4 divers) over an 8-hour day is estimated as follows:

Dive suit/scuba rental	$600
Air for scuba	50
Labor	4600
Boat Charter	500
Decompression Chamber	1200
Total	$6750/day

6.1.2 Explosive Operations

(No estimate is provided for the costs to obtain the necessary safety submissions and approvals). Federal regulations (29 CFR 1910.109 and 1926.912) govern safe practices for the storage of explosives and underwater blasting. Divers will require a portable magazine (ready service locker) to store HL-21s and other explosive material, estimated at a capital expense of $5000. Divers will require detonation and support equipments including lines, augers, detonators, galvanometer, and blast machine, estimated at a capital expense of $2000. The cost of the HL-21 is estimated at $100/unit. Once UXO has been low-ordered, the explosive waste must be stored at a permitted range, packaged/classified, and certified safe for transport (by a military official) to a permitted site. R and R Trucking (Joplin, MO) transportation costs for explosive wastes are estimated at $1.47/mile for loads less than 1000 pounds. Safety Kleen (Colfax, LA) has a minimum treatment fee of $1600, otherwise charging $3.85 to $4.67/ pound for treatment of class 1.1D explosive wastes.

6.1.3 Environmental/Safety Surveillance and Issues

Explosive operations may require a Medivac helicopter on standby, at an estimated expense of $1000/hour. Explosive operations may require range safety boat(s) to keep pleasure craft away from the operating area, at $400/day. Helicopter surveillance may be necessary to ensure endangered species are clear of the area (eg. gray whales, green sea turtles, etc.) The rental cost for a Hughes 500 helicopter is estimated at $650/flying hour.

6.2 Cost Comparison to Conventional Technologies

The following is offered as a cost to compare conventional BIP to low-order detonation based on the low-order detonation of a Mk 82 bomb with a reduced yield of 99%:

- Dive operations

Dive operations are expected to incur similar costs for BIP or low-order operations. Divers are expected to take an additional 20 minutes to police up the area after a low-order detonation. However, this time will be more than offset by the 95% reduction in area that must be surveyed by divers for dead or injured fish/marine mammals on the sea floor.

- Explosive Operations.

A pentolite booster (5#) used as a BIP donor charge is estimated at $20, the HL-21 is estimated at $100. Most other demolition set up and material costs would be shared. Low-order operations are expected to incur significant costs over BIP for the transportation, storage, shipment, and treatment of the 140 pounds of high explosive residue. The incremental cost to package, transport 500 miles and treat this waste is estimated at $1350.

- Environmental/Safety Surveillance

Because low-order detonation techniques are not 100% reliable, environmental surveillance will still be required out to the ranges expected for high order detonation. All other expenses are expected to be shared costs.

7 Regulatory Acceptance

Regulatory agencies were not involved during the course of the study.

8 Technology Implementation

8.1 DoD Need

The results of a Navy-initiated survey to identify current and former ranges are still pending. This survey will not include former dumpsites or other coastal areas where abandoned ordnance may have been deposited. It is postulated that UXO is likely in all ports where Navy ships have operated. Current efforts to remediate underwater UXO have been limited. The ongoing efforts at Ft. Jackson, WA, do not require BIP procedures. The efforts to cleanup Mare Island and San Diego shipping channel in CA have been limited in scope as site investigation and alternatives are being studied. **H. R. 3212** (proposed), the 'Underwater Unexploded Ordnance Removal Act of 2001,' will require the Secretary of Defense to expand the range maintenance program of the Department of Defense to include the removal of unexploded ordnance from any underwater portions of live impact areas.

8.2 Transition Plan

Additional efforts have been proposed to ESTCP by NAVEODTECHDIV to address the data gaps identified in Section 5.2.3. Completion of this additional testing and the conduct of field trials may be necessary before low-order techniques gains regulatory and commercial acceptance as a viable alternative to BIP.

A draft Notional Concept has been informally provided to EOD Group TWO, Norfolk, VA for consideration. A Notional Concept would be the initial step to a formal program to adapt existing Navy tools (shaped charges unavailable to commercial concerns) to underwater low-order detonation procedures for UXO. The HL-21 is currently not approved for Navy use.

9 Lessons Learned

9.1 Next Demonstration

The principle lesson learned during this study was that a low-order procedure should be developed before going though the expense of instrumentation. The 155m projectile procedure was developed at Blossom Point prior to the instrumented testing at ATC. The Mk 82 bombs were too large to be tested at Blossom Point. It may have been worthwhile to develop an HL-21 procedure at ATC or Fort A. P. Hill prior to the start of instrumentation trials.

9.2 Other Demonstrations

A principle lesson from this study to others is that the shipment of ordnance and explosives can take extraordinary amounts of time.

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Appendix A   Points of Contact

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Appendix B Data Archiving

The study data has been archived on CD at Aberdeen Test Center. Contact Joe Nokes, Test Manager within the Maritime Test Team, at 410.278-6945, x250, or email at jkopczy@atc.army.mil.

The TechDemo Plan is available from the Project Manager, Andy Pedersen

Appendix C HL-21 BROCHURE

HL 21 The New Low Order Technique Standard

The TDW solution:

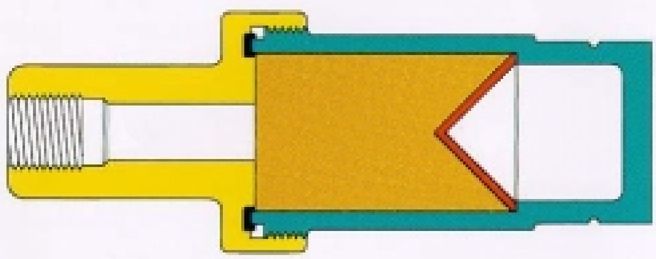
TDW's Low Order Technique application:
TDW's experience in the field of shaped charge technology. The experience gained in over three decades forms the basis of this new system for quick and effective clearing of unexploded ordnance and drift munitions from mine fields, test ranges and military combat fields.

HL 21 - The new TDW procedure used in the Low Order Technique meets all requirements, even in complicated situations and under severe conditions.

Characteristics:

- Antimagnetic
- Contact-free arrangement at a distance of up to 350 mm (14 in.).
- Can be used under water at depths of up to 60 meters.

System reliability has been proven in numerous comprehensive tests.



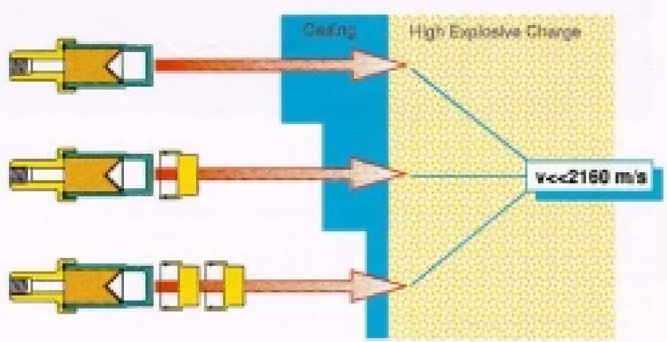
Technical Data:

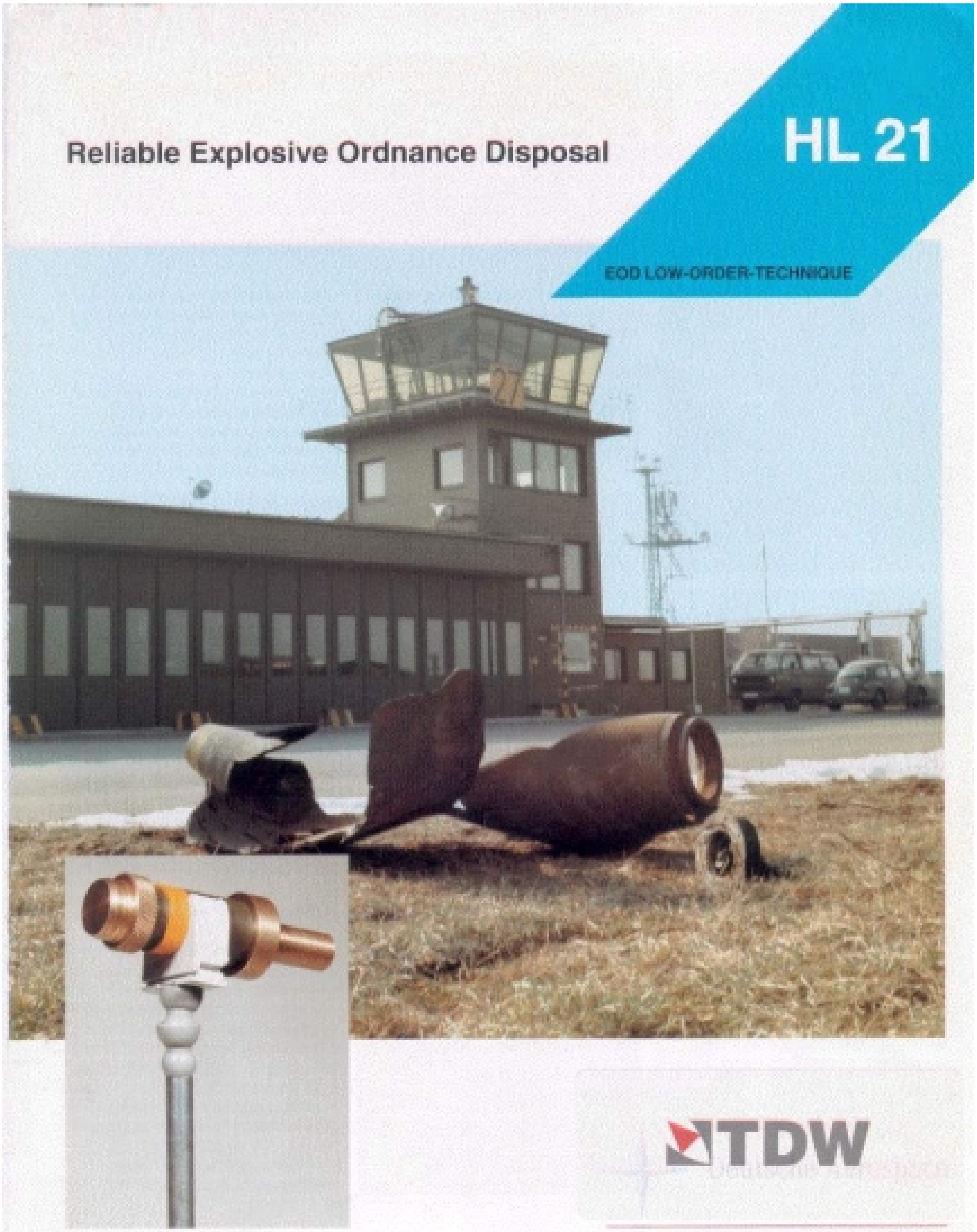
Device dimensions	
Diameter	32 mm
Length	95 mm
Mass	140 g
Charge	
Type	HWC Shaped Charge
Mass	18 g
Liner	copper cone
Barrier	10 mm Brass

The Low Order Technique:

permits destruction of the unexploded charge (combustion, breakup into major pieces, the maximum effect being a deflagration) without essential risk to the surroundings.

Barriers permit an individual adjustment of the HL 21 to various wall thicknesses found in drift munitions and guarantee effective disposal.




Reliable Explosive Ordnance Disposal
HL 21
EOD LOW-ORDER-TECHNIQUE
TDW

Appendix D   Analytical Methodology

Introduction

This appendix describes the procedure used to analyze the low-order test data measured at Briar Point UNDEX Pond. The 155mm projectile contains 14.6 lbs of TNT while the Mk 82 bomb has 192lbs of tritonal, which is equivalent to 243 lbs of TNT. The goal was to determine an equivalent TNT weight using two different methodologies. Five different pressure history parameters are used to assess an equivalent TNT weight:

1. Maximum shock pressure
2. Maximum shock impulse
3. Maximum bubble pressure
4. Maximum bubble impulse
5. Bubble period.

The two different methods used to relate the values of these parameters to TNT equivalent weight are Similitude and a 1-D Euler equation solution. Similitude is a set of empirical formulas relating peak shock pressure and shock impulse to charge weight and range. The 1-D Euler solution is obtained by solving the Euler equations in spherical coordinates and provides pressure as a function of time on a finite difference grid.

Data Processing

The measured data consist of pressure-time traces along three axes at several ranges. This data is processed to determine peak shock pressure, peak bubble pressure, maximum shock impulse, maximum bubble impulse, and bubble period. To facilitate automation, separate shock and bubble time windows were defined, as shown in Figure D-1. The maximum shock pressure and shock impulse are the peak values of these parameters over the shock time window, while the maximum bubble pressure and impulse are the peak values obtained over the bubble time window. The bubble period is the time of maximum pressure in the bubble window. The bubble maximum impulse is adjusted by subtracting the minimum impulse. This is necessary since the impulse at the start of bubble collapse pulse is not zero. The widths of the shock/bubble windows are (0,60ms)/(130ms, 260ms), respectively, for the 155mm projectile and (0,80ms) / (120ms, 420ms) for the Mk 82 tests.

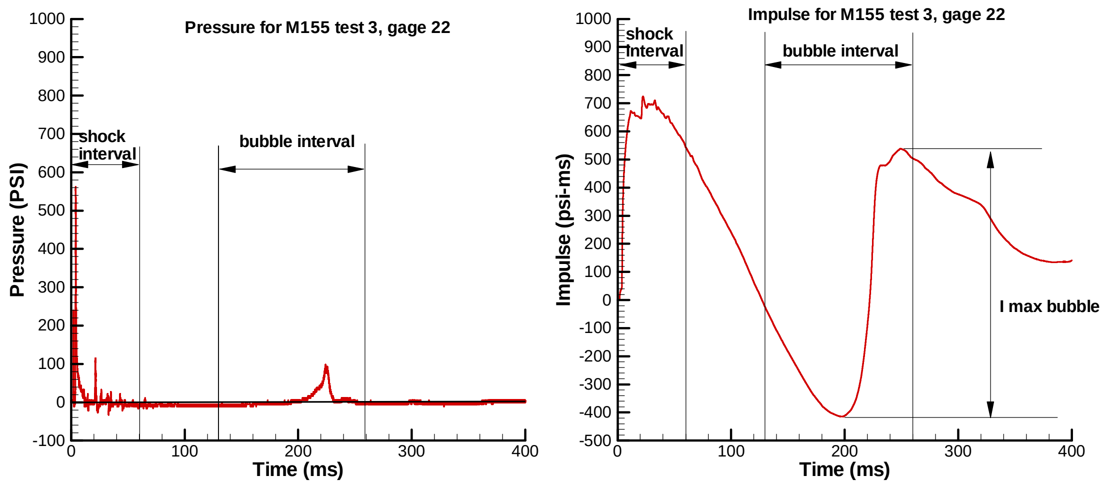


Figure D-1. Pressure History Parameters

Impulse is calculated from

$$I(t) = \int_0^t (p - p_\infty) dt$$

Here p_∞ is the baseline pressure that is estimated from:

$$p_\infty = \frac{1}{T} \int_0^T p dt$$

and T=1 ms.

The values of maximum pressures, maximum impulses and bubble period resulting from this data reduction process suggests that results are independent of orientation and hence data was analyzed by range only.

Calculation of Equivalent Weight

The equivalent weight is calculated by two different methods. The similitude relations (Price, 1979) provide explicit equations for charge weight as a function of peak shock pressure and maximum shock impulse. The 1-D Euler solution also yields the relation between charge weight and bubble peak pressure or bubble impulse.

The similitude relations for TNT weight in pounds, W, are as follows:

Peak shock pressure, P_{max} : $W = R^3 \left[\frac{P_{max}}{K_1} \right]^{\frac{3}{A_1}}$ (1)

Maximum Impulse, I_{max}: $$W = \left[\frac{I_{max} R^{A_3}}{K_3} \right]^{\frac{3}{1+A_3}} \qquad (2)$$

The values of the constants are K_1=22,505, A_1=1.18, K_3=1.798, and A_3=.98. The values of A_3 and K_3 represent maximum impulse over a time range of 7θ.

To compute the equivalent weight of TNT from the experimental data, insert measured values of P_{max} and I_{max} into equations (1) to (2), respectively.

1-D solutions to the Euler equations are computed using the 1-D Godunov solver (Wardlaw, 1998). This technique uses a second order Godunov method in spherical coordinates. The explosive gas is modeled with the JWL equation of state, the water is modeled with Tait, and the calculation is initiated with a constant volume detonation. A unique feature of this computational procedure is that the interface between the water and gas is tracked; the mesh is adjusted after each time step to eliminate partial cells from the calculation.

The Euler equations scale as follows:

T=t/L
X=x/L
P=p
U=u
R=ρ
I=I/L

where t=time, x=range, p=pressure, u=velocity, ρ=density and I=impulse are the dimensional values and T, X, P U, R and **I** are the corresponding non-dimensional quantities. L is the characteristic dimension or equivalently, $W^{(1/3)}$. A consequence of this scaling is that any solution can be used to predict the results for an arbitrary explosive weight, simply by applying the above scaling. The sole dependency is ambient pressure, which does not have a significant effect on the shock but strongly impacts the bubble. Hence for the present study, a single Euler solution is needed, since all tests were carried out at a depth of 24ft.

Appendix E   HL-21 Procedure

The reader is further cautioned that this information does not constitute a "validated and verified" EOD procedure.   This section does describe the HL-21 procedure used in the ESTCP Study. *Low-order detonation techniques should not be attempted where the consequences of an inadvertent high-order detonation cannot be tolerated.*

The HL-21 produces a shape charge jet that will travel through water, penetrate the case of the ordnance item, and initiate a low-order reaction. Low-energy M-6 Blasting Caps were used to initiate the tool. (High-energy detonators (exploding bridgewire detonators) can also be used). Silicon RTV was used to keep any water from getting in between the M-6 cap and the HL-21.

Ordnance was attacked perpendicular to the surface, near the ogive, and away from any lug, ports or fuzing. See figures E-1 and E-2 for pictures of typical test set-ups. The point of attack is not critical, but should be near the mid-section at an area of minimum case thickness. (The 155mm projectile was attacked where the case thickness was nominally 14mm. The Mk 82 was attacked where the case thickness was nominally 12.5 mm).   Because the shots were prepared on the surface and lowered to a depth of 24 feet, extra care was taken to ensure that the set-up did not shift:

Figure E-1. 155mm Projectile Set Up

Figure E-2. Mk 82 Bomb Set Up

> The HL-21 was held by a plastic stand attached to a bent, fabricated flat bar.   The flat bar was securely held by band clamps around the ordnance. Duct seal (a soft, pliable material) and plastic tie wraps were used to secure the HL-21 to the plastic stand. (Metal band clamps or dense materials should not be in contact with the outside of the HL-21 in order to preclude any possible disruption to jet formation).

Total Molding Concepts of Winchester, VA, (540) 665-8408, produced the plastic stand that was used in the trials. The stand is produced for use with a variety of EOD tools. The stand that comes with the HL-21 would probably suffice in a field environment. Some consideration to the set up would be required with either stand for soft muds or strong currents.

The standoff distance between the face of the HL-21 and the surface of the ordnance is a *critical parameter* in using the HL-21 to attack UXO. The standoff distance will determine the velocity of the shaped charge jet when it impacts the bulk explosive load of UXO. The standoff distance used for all 155mm projectile shots was 60 mm with an estimated precision of +/- 1mm. Several standoff distances were tried for the Mk 82 bombs, varying from 30 to 60 mm, again with an estimated precision of +/- 1mm. The 33mm standoff was used with success, although a high-order detonation did occur with this standoff. A dowel rod cut to the desired length was used to set the stand off distance for each shot, seen in figure E-2. The dowel rod was removed before the shot. (A more desirable alternative would be to use a spacer that could be left in place and not affect the jet). The manufacturer recommends that two or more HL-21s be used on larger ordnance, but this configuration was not tested.